Recent Advances in Plastic Packaging of Flip-Chip and Multichip Modules (MCM) of Microelectronics

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***Abstract*—The success in consumer electronics in the 1990's will be focused on low-cost and high performance electronics. Recent advances in polymeric materials (plastics) and integrated circuit (IC) encapsulants have made high-reliability very-large-scale integration (VLSI) plastic packaging a reality. High-performance polymeric materials possess excellent electrical and physical properties for IC protection. With their intrinsic low modulus and soft gel-like nature, silicone gels have become very effective encapsulants for larger, high input/output (I/O) (in excess of 10 000), wire-bonded and flip-chip VLSI chips. Furthermore, the recently developed silica-filled epoxies underfills, with the well-controlled thermal coefficient of expansion (TCE), have enhanced the flip-chip and chip-on-board, direct chip attach (DCA) encapsulations. Recent studies indicate that adequate IC chip surface protection with high-performance silicone gels and epoxies plastic packages could replace conventional ceramic hermetic packages. This paper will review the IC technological trends, and IC encapsulation materials and processes. Special focus will be placed on the high-performance silicone and epoxy underfills, their chemistries and use as VLSI device encapsulants for single and multichip module applications.**

***Index Terms*—Encapsulants, epoxies, flip-chip, multichip modules, silicones, underfills.**

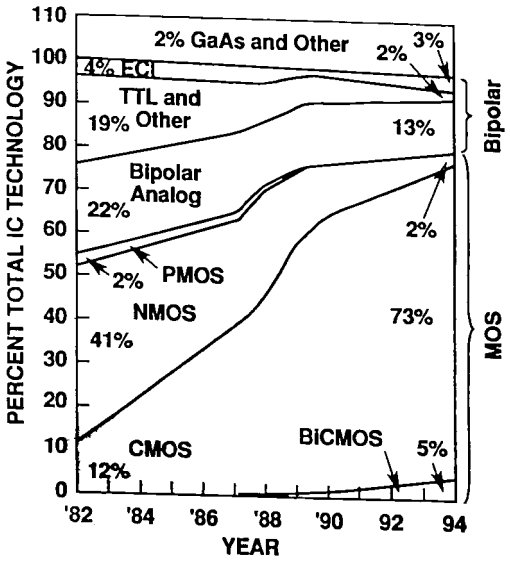

Fig. 1. CMOS IC technology trends.

I. Introduction

ADVANCES in electronic technology have had great technological and economic impact on the electronic industry throughout the world. The rapid growth of the number of components per chip, the rapid decrease of device dimension, and the steady increase in integrated circuit (IC) chip size have imposed the stringent requirements, not only on IC physical design and fabrication, but also in electronic packaging and interconnects [1]–[4]. Nonhermetic plastic packaging is one of the most common processes to encapsulate and protect these electronic components. With advances in very large scale integration (VLSI) technology and the multichip modules packaging, encapsulation of this high density packages has become a challenge. Various polymeric encapsulants are used for encapsulating these type of electronic components. Silicone and epoxy are two key materials and their processes will be discussed in detail in this paper.

Manuscript received December 6, 1995; revised September 30, 1998. This paper was presented at the Second International Symposium on Electronic Packaging Technology, Xi'an, China, October 1995. This paper was recommended for publication by Editor C. P. Wong upon evaluation of the reviewers' comments.

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Publisher Item Identifier S 1521-3331(99)01992-3.

II. Materials Requirements

The purpose of encapsulation is to protect the electronic components from adverse environments, thermal shock, temperature cycle during actual life applications, improve handling in downstream assembly processes; prevent mobile ion contaminations; and increase the long-term reliability of electronics with a reasonable cost. High performance and low cost plastic materials are the principal driving force in the 1990's. Electrooxidation (corrosion) and metal migration are the major cause of IC failures. These are attributed to the presence of moisture. When enough moisture diffuses through the encapsulant to form a continuous water path at the substrate interface, with the presence of mobile ion(s) and under electrical bias, electrocorrosion begins. Mobile ions, such as sodium and potassium, tend to migrate the p-n junction of the IC device where they acquire an electron, and deposit as the corresponding metal on the p-n junction, consequently this destroys the device. CMOS is likely to be the trend of the VLSI technology (see Fig. 1) and sodium chloride is a common contaminant. The protection of these devices from the effects of these mobile ions is an absolute requirement. The use of an ultra-high purity encapsulant to encapsulate the passivated IC device is the answer to some of these mobile ion contamination problems.

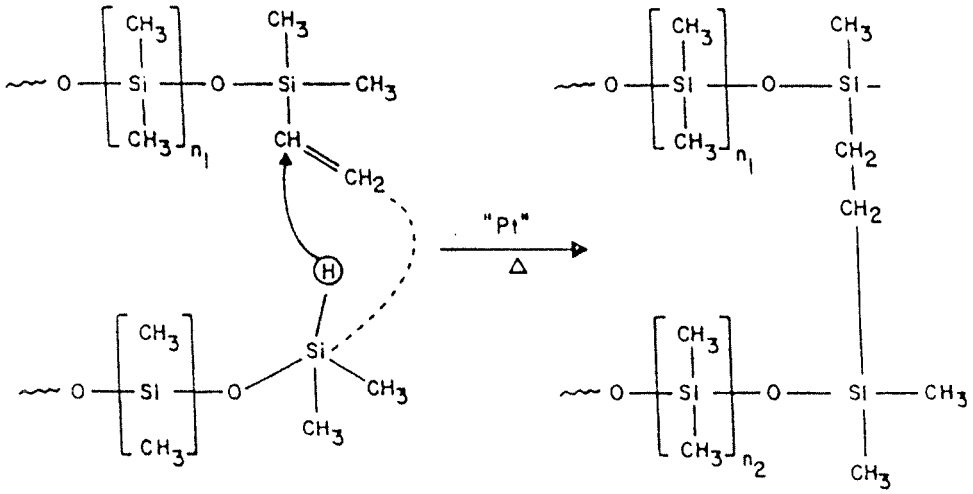

Fig. 2. Heat curable silicone elastomer.

Hostile environments, such as extreme cycling temperature (values from −65 to +150 °C in US Mil Spec 883), high relative humidity (85–100%), shock and vibration, and high temperature operating bias are part of the real life operation, and the device must survive these operation-life cycles. In addition, encapsulants must also have suitable mechanical, electrical and physical properties, such as minimal stress and matching thermal expansion coefficient, etc., which are compatible to the IC devices. Furthermore, the encapsulant must have a love dielectric constant to reduce the device propagation delay, excellent thermal conductivity to dissipate those power hungry, high-speed bipolar IC, and high density packaging which generate tremendous amounts of heat that require special thermal management considerations. Since the encapsulation is the final process step and some of the devices are expensive, particularly in the high density multichip modules (MCM), it must be easy to apply and repair in production and service. With the proper choice of encapsulant and process, the encapsulation enhances the reliability of the fragile IC device, and improves its mechanical and physical properties and its manufacturing yields. These are the ultimate goals of the encapsulation and packaging.

III. Materials for Microelectronic Encapsulations

There are many polymeric materials with suitable electrical, chemical, and physical properties that could be used as electronic components encapsulation. However, only a few such as silicones, epoxies, polyimides, and benzocyclobutenes are widely used today.

A. Silicones

With a repeating unit of alternating silicon–oxygen, the siloxane chemical backbone structure, silicone possesses excellent thermal stability and flexibility that are superior to most other materials. Polydimethylsiloxane provides a very low glass transition temperature ($T_g = -125$ °C), the lowest in all polymeric materials, but is also T suitable for use at temperatures up to 200 °C. Three methods of cross-linking are used in this system:

1) condensation cure systems;
2) additional cure systems;
3) peroxide free-radical cure systems.

For electronic applications, only the high purity room temperature vulcanized (RTV) condensation cure silicone which uses an alkyoxide cure system with noncorrosive alcohol by-products, and platinum-catalyzed addition heat-cure (hydrosilyation) silicone systems are suitable for device encapsulation (see Fig. 2) [2].

B. Epoxies

The unique chemical and physical properties such as excellent chemical and corrosion resistances, electrical and physical properties, excellent adhesion, thermal insulation, low shrinkage, and reasonable material cost have made epoxy resins very attractive in electronic applications. State-of-the-art, high purity epoxies contain greatly reduced amounts of chloride and other mobile ions, such as sodium and potassium, and have become widely used in device encapsulation and molding compounds. The incorporation of large loading (>75% by wt) well-controlled spherical silica particles with size and shape distribution as filler in the epoxy systems has drastically reduced the thermal coefficient expansion for these materials and makes them more compatible with the IC die-attached substrate materials. The incorporation of a small amount of an elastomeric, carboxyl-terminated butyldiene (CTBN) type domain particles, to the rigid epoxy has drastically reduced the elastic modulus, reduced the thermal stress, and increased the toughness of the epoxy material. This new type of low stress epoxy encapsulant has great potential application in molding large IC devices when the epoxy materials are properly formulated and applied, and their stress related issues such as reduced stress and reduced thermal coefficient of expansion have been properly considered and resolved. The recently developed epoxies with TCE matching of the flip-chip solder joints enhanced the thermal cycling reliability of

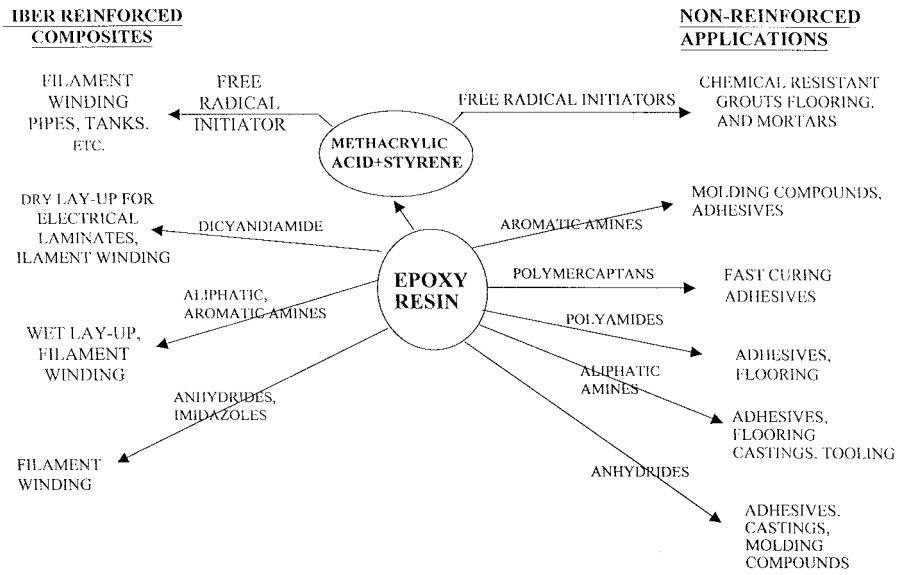

Fig. 3. Epoxy resins in structural applications.

resin devices. The general reactions of epoxies are shown in Fig. 3.

IV. Material Processes

Material processes consist of cavity-filling and saturation coating. The cavity-filling process involves molding, potting, and underfilling of flip-chip solder joints, and saturation which consists of conformal coating, spray, and dip coatings. Molding is the most widely used plastic packaging, it accounts for over 90% of world-wide IC production. However, flip-chip underfills attract the most current R&D interests due to their temperature cycling solder joints fatigue enhancement, in particularly the no flow underfills. These will be discussed as follows.

A. Molding

Molding is the most cost-effective and high performance plastic packaging method for IC devices. A polymeric resin (one of the thermosetting molding compounds) is injected into a mold and then cured, i.e., the process involves two steps:

1) molding compound is preheated until it melts and the resin flows through runners, gates, and finally fills up the cavities;
2) resin is cured and released from the mold in predetermined shapes (see Fig. 4).

The exact control of the mold pressure, viscosity of the molten molding compound, and the delicate balance of runners, gates, and cavity designs are critical in optimizing the molded plastic IC. Finite element analysis of the plastic molding process is becoming an integral part of improving this process. Since the shear stress of the IC chip molded component could cause wire-bond sweep, device passivation cracks, top-layer metallization deformation, and multilayer oxide and nitride cracks, improved molding compounds and processes could eliminate the damage to the molded IC devices. These molding

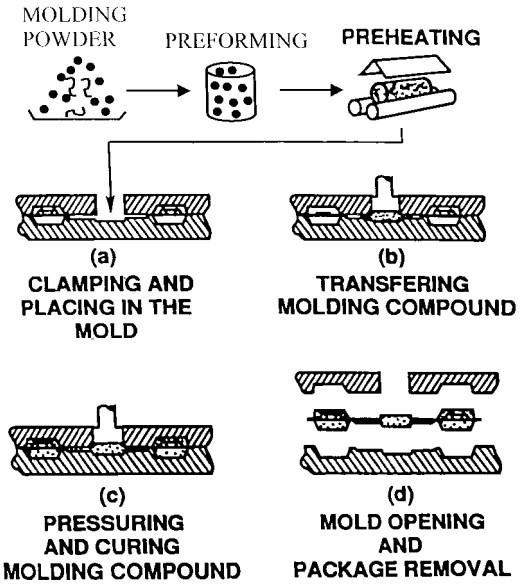

Fig. 4. Transfer molding process.

techniques are well-documented in the literature [6]. Pressure injection and conformal moldings are some of the current molding processes. With new advances of low stress molding compounds, techniques such as transfer molding, aperture plate molding, and reactive injection molding are in production use and provide economic ways to encapsulate and package IC devices.

B. Underfill Flip-Chip Solder Joints

Due to its high I/O interconnect density, flip-chip interconnect is the major technology of the high performance IC in the 1990's and beyond. Polymeric underfill encapsulants such as high loading of silica filled epoxies, enhance the flip-chip solder joints reliability and become very attractive for the plas-

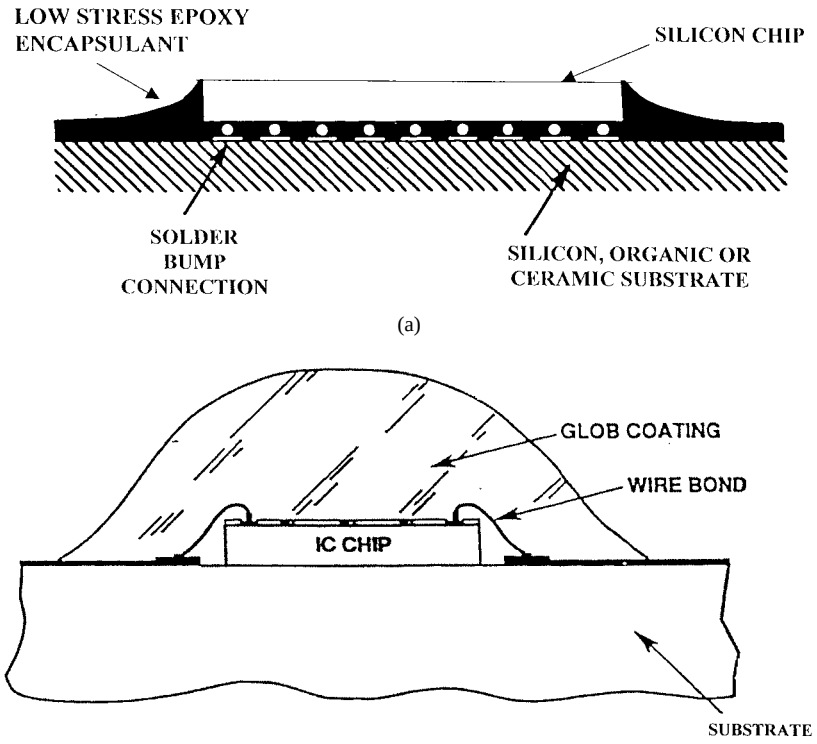

Fig. 5. Encapsulated flip-chip device.

tic packaging of direct chip on board applications. The key to enhance the thermal cycling performance for the underfill flip-chip materials are excellent adhesion, resonable high modulus, and their thermal coefficient expansion (TCE) closely match with the solder joints. Furthermore, the encapsulant evenly distributed the shear stress of these joints to larger surfaces that enhanced the thermal cycling of flip-chip devices [7], [8]. Very recently, a novel no flow underfill and process was developed for the small standoff, large IC die on FR4 printed wiring board applications [9]. This type of material and process could save the next generation of low-cost flip-chip application as much as 40% [10].

V. Recent Advances in Hermetically Equivalent IC Packaging

Recent advances in IC encapsulants and polymeric materials have made high-reliability VLSI plastic packaging a reality. Epoxy (plastic) molded devices have shown excellent reliability, and they are well documented in the literature. However, recent advanced in hermetically equivalent packaging have been centered on the use of soft silicone gel [2]. Although devices are typically protected with passivation layers consisting of SiO_2 or Si_3N_4, these layers are not 100% pinhole-free. Also, the "edge effect" around wire bonding pad areas of the IC device after wirebonded requires additional protection. A spectrum of numerous potential encapsulation materials exist. However, for high reliable IC device encapsulant, only a selected few encapsulants, as mentioned earlier in this paper, are potential candidates. Two important mechanical properties play an extremely strong role in the overall reliable functionality of the encapsulated device. The two properties are thermal coefficient of expansion (TCE) and modulus of elasticity (E). These properties give rise to detrimental thermal cyclical stress as where k is a constant, dT is the difference of the cycle temperatures (T_1 and T_2)

$$\text{stress} = k \int_{T_1}^{T_2} (\Delta\text{TCE}) \cdot E \cdot dT.$$

As we all know, high performance silicone gel possesses excellent electrical and physical properties for IC protection. With their intrinsic low modulus and soft gel-like nature, silicone gels have become very effective encapsulants for larger, high I/O, wire-bonded VLSI chips. Recent studies indicate that adequate IC chip surface protection with high-performance silicone gels in plastic packaging could possibly replace conventional ceramic hermetic packaging, when IC devices are properly cleaned and silicone gels are properly processed, they can achieve the reliability of ceramic hermetic packaging [2], [5], [11].

At AT&T, we have replaced the ceramic hermetic gated diode crosspoint (GDX), a solid-state high voltage switch used in AT&T's no. 5 electronic switching system (ESS), with a flip-chip bonded GDX on a ceramic substrate. This flip-chip bonded multichip module used a 95/5 (Pb/Sn) solder for interconnection. A silicone gel was used to coat (glob) the GDX device and further coated with a silicone elastomer for mechanical protection. This GDX HIC is operated at 375 V at AT&T's no. 5ESS central office switch system with ultrahigh reliability [9].

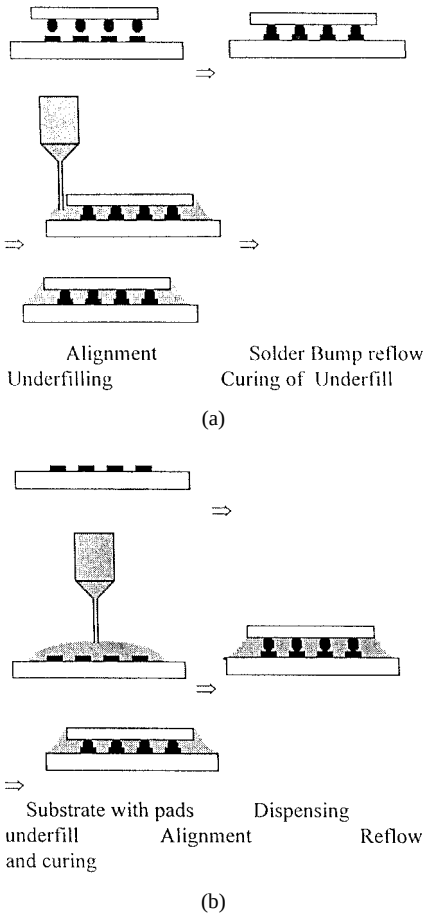

Fig. 6. (a) The conventional underfilling process and (b) the no-flow underfilling process.

Furthermore, the recent advances in epoxy underfill materials [7]–[9] provide an excellent temperature cycling reliability for the flip-chip bonded devices on a FR-4 substrate (see Figs. 5 and 6).

Flip-chip [12] MCM packaging is becoming an essential approach in high-density packaging, not only for meeting high operation speed requirements, but also for improving system integration. Because of the ever-increasing large MCM sizes, larger than 4 in^2, pressure seals are very expensive and technically difficult, if not consistently impossible. The use of silicone gel or elastomer and epoxy underfills as nonhermetic packaging can be a simple solution. In addition, the use of silicone gel and polyimides as a large VLSI chip passivation could provide a stress-relief buffer coating of the post-molded packages and achieve hermetically equivalent reliability. Clearly, the use of multichipping instead of wafer scale integration will have an important impact on the applications of nonhermetic packages.

VI. Conclusion

Recent advances in high-performance polymeric materials, such as improved silicone elastomers, ultrasoft silicone gels, low-stress epoxies, and high-performance epoxy underfill materials have provided materials in the areas of low dielectric constants, high breakdown voltage strength, high sheet resistance, and less dielectric change with humidity will continue to require the developing of high-performance polymeric materials. Their application in on-chip interconnections, wafer-scale integration, high-performance system integration architecture structures with high speed, controlled-impedance transmission lines, interconnecting networks, and high-performance packaging will become apparent. It is a challenge that demands collaborative innovative efforts among polymer chemists, materials scientists and device and packaging design engineers.

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C. P. Wong (SM'87–F'92), for a photograph and biography, see this issue, p. 5.

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